



# An anionic surfactant-assisted equilibrium adsorption method to prepare highly dispersed Fe-promoted Ni/Al<sub>2</sub>O<sub>3</sub> catalysts for highly selective mercaptan removal

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## ABSTRACT

This article proposes a novel sodium dodecylbenzenesulfonate (SDBS)-assisted equilibrium adsorption method for preparing highly dispersed Ni/Al<sub>2</sub>O<sub>3</sub> and Fe-promoted NiFe/Al<sub>2</sub>O<sub>3</sub> thioetherification catalysts. The proposed strategy anchors nickel cations onto the electronegative surface of an Al<sub>2</sub>O<sub>3</sub> support modified by negatively charged DBS<sup>−</sup> bilayers. As a result, this method achieves highly dispersed Ni nanoparticles without strengthening the metal-support interaction, promoting the reducibility and sulfurization of the supported Ni species. The as-prepared Ni-based catalysts have a smaller size, a higher dispersion of metal nanoparticles, and a greater amount of active metal sulfides than their counterparts prepared by the conventional impregnation method, endowing them with excellent catalytic performance for the highly selective removal of mercaptans. This method provides a new opportunity to prepare highly dispersed metal nanoparticles without a strong metal-support interaction.

## 1. Introduction

With increasingly stringent environmental regulations, the restrictions on the sulfur content of gasoline are becoming more and more stringent [1–4]. Mercaptans are the most detrimental sulfur-containing compounds in gasoline, not only because they are foul smelling and corrosive [5,6] but also because they can degrade gasoline quality by promoting the formation of gum [7]. Therefore, to produce clean gasoline, it is imperative to remove mercaptans from gasoline. The Merox sweetening process is the most typical technique for mercaptan removal. Although the improved fixed-bed sweetening technology has reduced the usage of sodium hydroxide, there is still a problem with the discharge of caustic dross [8,9]. Furthermore, mercaptans can also be removed by the hydrodesulfurization (HDS) technique, but this process saturates a large number of olefins that contribute to the octane number of gasoline; therefore, the HDS technique degrades the quality of the resultant gasoline product [10,11]. The thioetherification technique is usually carried out at low temperature under a H<sub>2</sub> atmosphere, in which the mercaptans in gasoline react with diolefins to form thioethers that can be removed in the subsequent process along with any sulfur-containing compounds with higher boiling points [12,13]. During the thioetherification process, the mercaptans in gasoline are removed while avoiding olefin saturation and maintaining the gasoline octane number.

Solid acids and sulfided transition metals have been applied to the thioetherification process [14,15]. Solid acid catalysts, such as sulfonic acid resin, solid phosphoric acid and intercalation compound, are effective catalysts for the thioetherification of mercaptans, but they are strong acid catalysts [14], which interact strongly with the basic nitrogen-containing compounds. Therefore, nitrogen-containing compounds are difficult to desorb from these strong acid sites, resulting in the deactivation of solid acid catalysts [14,16]. Sulfided transition metals (Ni, Pt, Pd and Ag) also have catalytic activity for the thioetherification of mercaptans [15,17,18]. In particular, low-cost nickel-based catalysts exhibit excellent sulfur and nitrogen resistance and good thioetherification activity [19], and thus, they have been applied in the thioetherification process [13]. In recent years, the Fe-promoted Ni/Al<sub>2</sub>O<sub>3</sub> catalysts were also investigated and they exhibited better catalytic activity than the monometallic Ni/Al<sub>2</sub>O<sub>3</sub> in the thioetherification for removing methyl and ethyl mercaptans [20]. For supported Ni/Al<sub>2</sub>O<sub>3</sub> catalysts, their activity and selectivity depend on the type and quantity of active sites, which are greatly affected by the dispersion and reduction degree of metal particles. Akande et al. reported that the reduction degree of nickel species is strongly affected by the nanoparticle size of nickel oxides: smaller nanoparticles can lead to a higher reduction degree and confer the synthesized catalysts with improved catalytic performance [21].

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In general, the incipient wetness impregnation method, nickel-alumina co-precipitation method and sol-gel method are the main approaches for synthesizing nickel-based catalysts [22–24]. The catalysts prepared by traditional impregnation method have large metal Ni particles, resulting in inferior utilization of nickel species [25]. Although the co-precipitation and sol-gel methods are desirable for increasing the dispersion of nickel species, the strong metal-support interaction results in a substantial increase in the difficulty in nickel reduction and sulfidation [26]. Li et al. investigated nickel species, nickel particle size, and nickel reducibility over three nickel catalysts prepared by the co-precipitation, sol-gel, and impregnation methods. Their results showed that the co-precipitation and sol-gel methods strengthened the interaction between the nickel species and alumina support and generated a large amount of  $\text{NiAl}_2\text{O}_4$  spinel phase, which is detrimental to the subsequent formation of the active phase [26].

In addition, Zhu et al. reported that the plasma treatment method is conducive to decreasing the nickel particle size and improving nickel dispersion, but it still suffers from the problem of the enhancement of the metal-support interaction [27]. Seo et al. proposed a single-step sol-gel and subsequent  $\text{CO}_2$  supercritical drying method that is suitable for producing well-dispersed  $\text{Ni}/\text{Al}_2\text{O}_3$  catalysts with uniformly distributed nickel nanoparticles, but this method is performed under high pressure and requires a high-cost device [28]. In summary, the preparation of  $\text{Ni}/\text{Al}_2\text{O}_3$  catalysts with high metal dispersion and a weak metal-alumina interaction remains a great challenge.

Herein, we proposed a sodium dodecylbenzenesulfonate (SDBS)-assisted equilibrium adsorption (SDEA) method to prepare highly dispersed  $\text{Ni}/\text{Al}_2\text{O}_3$  and  $\text{NiFe}/\text{Al}_2\text{O}_3$  catalysts without strengthening the metal-support interaction. In this method, the negatively charged  $\text{DBS}^-$  ions could form self-assembled bilayers on the  $\text{Al}_2\text{O}_3$  surface; one negative charge in these bilayers is connected with the electropositive  $\text{Al}_2\text{O}_3$  surface, and the other negative charge is exposed, which converts the positively charged  $\text{Al}_2\text{O}_3$  support into a negatively charged  $\text{Al}_2\text{O}_3$  support modified by  $\text{DBS}^-$  ( $\text{Al}_2\text{O}_3\text{-DBS}$ ). Therefore,  $\text{Ni}^{2+}$  ions can be anchored to the electronegative surface of  $\text{Al}_2\text{O}_3\text{-DBS}$  via electrostatic adsorption. Meanwhile, this method weakens the metal-support interaction and reduces the formation of nickel-aluminium spinels because it decreases the direct interaction between Ni species and the alumina support. As a consequence, the high dispersion of the supported nickel species does not depend on the metal-support interaction. The as-prepared Ni-based catalysts featured highly dispersed Ni nanoparticles with enhanced reducibility and sulfurization degree and thus exhibited excellent performance in the selective removal of mercaptans.

## 2. Experimental

### 2.1. Materials

The shaped  $\text{Al}_2\text{O}_3$  support was obtained from Shandong Alumina Plant (PR China). Nickel nitrate ( $(\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O})$ , 99%), ferric nitrate ( $(\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O})$ , 98%), sodium dodecylbenzenesulfonate (SDBS, 98%) and hydrochloric acid (HCl, 37%) were purchased from J&K Chemical Technology Company, Ltd. (PR China). 1-Propanethiol, 1-butanethiol, iso-butanethiol, t-butanethiol, 1-pentanethiol, 1-octene, isoprene, octane, toluene, carbon disulfide ( $\text{CS}_2$ ) and cyclohexane were purchased from Aladdin Biochemical Company (PR China) and used directly without any further purification.

### 2.2. Catalyst preparation

The preparation of the Ni-SDEA catalyst involves the following steps: 1.0 g of  $\text{Al}_2\text{O}_3$  was added into 70 mL of deionized water, and the resulting suspension was adjusted to pH = 5.0 by HCl. Then, 4.68 g of SDBS was slowly added, the suspension was magnetically stirred until SDBS dissolved completely, and the mixture was acidified to pH = 5.0 by HCl. Subsequently, 1.30 g of  $\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$  was added into the

mixture and then stirred for 4 h at 25 °C. The resulting mixture was placed in a 100 mL autoclave and heated at 120 °C for 24 h under rotation. Next, the sample was filtered, washed with deionized water until pH 7 was reached, and dried at 120 °C overnight. Subsequently, the sample was calcined in muffle furnace at a ramp rate of 2 °C/min from room temperature to 500 °C and maintained at this temperature for 4 h. The calcinations were carried out in muffle furnace without the introduction of flowing air. The obtained product is denoted Ni-SDEA.

For comparison, the Ni-IM catalyst was prepared by incipient wetness impregnation as follows:  $\text{Al}_2\text{O}_3$  was impregnated with a  $\text{Ni}(\text{NO}_3)_2$  aqueous solution. Then, the sample was prepared using the same drying and calcination steps as those described for Ni-SDEA. According to the inductively coupled plasma (ICP) results, the NiO loadings of Ni-SDEA and Ni-IM were 13.8 and 14.0 wt.%, respectively.

The loading of Fe in the Ni-SDEA and Ni-IM catalysts was carried out by impregnating Ni-SDEA and Ni-IM with  $\text{Fe}(\text{NO}_3)_3$ . The impregnated samples were dried at 120 °C overnight and calcined at 500 °C in air for 4 h. The obtained products were denoted NiFe-SDEA and NiFe-IM. The  $\text{Fe}_2\text{O}_3$  contents in NiFe-SDEA and NiFe-IM were 6.0 and 5.9 wt.% (determined by ICP analysis), respectively.

The Fe-IM catalyst was prepared by impregnating  $\text{Al}_2\text{O}_3$  with a  $\text{Fe}(\text{NO}_3)_3$  aqueous solution. The sample was prepared using the same steps as those described for Ni-IM. The  $\text{Fe}_2\text{O}_3$  loading of Fe-IM was 6.1 wt.% (determined by ICP analysis).

The sulfided catalysts were obtained by sulfurizing the oxidic catalysts with 3 wt.%  $\text{CS}_2$  in cyclohexane at 230, 280, 300 and 320 °C respectively for 2 h in a fixed-bed microreactor. The sulfurization processes were performed at 2.0 MPa, a liquid hourly space velocity (LHSV) of  $4 \text{ h}^{-1}$ , and a  $\text{H}_2/\text{oil}$  ratio of 300 (v/v). The oxidic catalysts are denoted as Ni-SDEA, Ni-IM, NiFe-SDEA, NiFe-IM and Fe-IM; the corresponding sulfided catalysts are denoted as NiS-SDEA, NiS-IM, NiFeS-SDEA, NiFeS-IM and FeS-IM.

### 2.3. Characterization

X-ray diffraction (XRD) was carried out on a Bruker D8 Advance X-ray diffractometer with Cu  $\text{K}\alpha$  radiation at 40 kV and 40 mA. The scanning rate was 5°/min over the angular range from 10 to 90°.  $\text{N}_2$  adsorption-desorption experiments were performed using a Micromeritics ASAP 2420 instrument. Prior to the adsorption measurement, the samples were evacuated at 250 °C overnight. The compositions of samples were determined by ICP on a PerkinElmer OPTIMA 7000 DV spectrometer. Before the measurements, the samples were dissolved in *aqua regia*. The zeta potentials of the samples were determined by a Zetasizer Nano ZS instrument. The ammonia temperature-programmed desorption ( $\text{NH}_3$ -TPD) experiments were carried out on a Builder PCA-1200 instrument. First, 0.1 g of the sample was heated from 30 to 600 °C under Ar (30 mL (STP)/min), and the temperature was kept at 600 °C for 0.5 h. Then, the quartz reactor was cooled to 70 °C in Ar, and  $\text{NH}_3$  (30 mL (STP)/min) was passed into the reactor at that temperature for 20 min; subsequently, the sample was purged with Ar at 70 °C for 90 min to remove the physically adsorbed  $\text{NH}_3$ . Finally, the sample was heated to 600 °C in an Ar flow at a heating rate of 10 °C  $\text{min}^{-1}$ , and the signal of the desorbed ammonia was recorded with a thermal conductivity detector (TCD). The hydrogen temperature-programmed reduction ( $\text{H}_2$ -TPR) experiments were performed on an AutoChem II 2920 (Micromeritics, USA). Typically, 0.1 g of the sample was pretreated in a quartz reactor at 450 °C for 2 h in an Ar flow (30 mL (STP)/min) and then cooled down to 60 °C. Subsequently, the sample was heated to 1000 °C in a 10 vol %  $\text{H}_2/\text{Ar}$  mixture (30 mL (STP)/min) at a heating rate of 10 °C  $\text{min}^{-1}$ , and a calibration curve of the TCD response signal expressed by the integrated area of the peak as a function of the amount of consumed hydrogen was established with a series of known amounts of pure CuO samples [29]. The CO chemisorption of the samples was carried out on AutoChem II 2920 (Micromeritics, USA). Typically, 0.2 g of the sulfided sample was heated at

300 °C for 2 h in a He flow (at 30 mL/min) and subsequently was cooled down to –50 °C. Then, pulse chemisorption measurements were conducted at –50 °C with 10% CO in He atmosphere. The H<sub>2</sub> chemisorption of the sulfided samples was carried out on AutoChem II 2920 (Micromeritics, USA). 0.2 g sample was introduced into a quartz reactor, and after reduction in H<sub>2</sub> at 500 °C for 2 h, the sample was kept at 500 °C for 30 min in a He flow. Then, the sample was cooled down to 25 °C. Pulse chemisorptions measurements were conducted at 25 °C with 10% H<sub>2</sub> in He atmosphere. To calculate metal dispersion, the adsorption stoichiometry of H/Ni = 1 was assumed [30]. X-ray photoelectron spectroscopy (XPS) analysis of the samples was carried out on a VG ESCA Lab 250 spectrometer using Al K $\alpha$  radiation with an energy resolution of 0.4 eV. The spectra were scanned at a pressure of  $3 \times 10^{-8}$  Pa. High-resolution transmission electron microscopy (HRTEM) was performed on an F20 microscope at an acceleration voltage of 200 kV. The size distribution of metal nanoparticles was determined by manual measurement of the particles in 20 HRTEM images from each sample. Energy dispersive spectroscopy (EDS) was performed on the energy dispersive X-ray instrument attached to the TEM system. The carbon content of the calcined catalyst was determined on a Leco CS600 carbon analyzer [31].

#### 2.4. Assessment of catalyst activity

The thioetherification activities were evaluated in a fixed-bed microreactor with a loading of 1.0 g of catalyst (20–40 mesh) using a mixture of mercaptan (0.048 wt.%), 1-octene (23.0 wt.%), isoprene (0.4 wt.%), octane (46.6 wt.%) and toluene (30.0 wt.%) as a model system. The reactions were carried out at 1.0 MPa, 135 °C (determined from Fig S1), a liquid hourly space velocity (LHSV) of 6 h<sup>–1</sup> (determined from Fig S2), and a H<sub>2</sub>/oil ratio of 30 (v/v) over the sulfided catalyst. The products were collected after a steady state was reached. The sulfur compounds in the products were analysed using a TSQ 8000 Evo GC–MS with an HP-5ms chromatographic column (60 m  $\times$  0.25 mm  $\times$  0.25  $\mu$ m). The hydrocarbon compositions in the products were analysed using an Agilent 1790 gas chromatograph (GC) equipped with a flame ionization detector (FID) and an HP-PONA capillary column (50 m  $\times$  0.20 mm  $\times$  0.50  $\mu$ m).

Mercaptan removal ratio ( $r_{mer}$ ) and olefin conversion ( $X_{ole}$ ) were defined as follows:

$$r_{mer} = \frac{\text{mass fraction of mercaptan in feed} - \text{mass fraction of mercaptan in product}}{\text{mass fraction of mercaptan in feed}} \times 100\% \quad (1)$$

$$X_{ole} = \frac{\text{mass fraction of olefin in feed} - \text{mass fraction of olefin in product}}{\text{mass fraction of olefin in feed}} \times 100\% \quad (2)$$

The turnover frequency (TOF) was used to evaluate the thioetherification activity. The TOF was calculated by the following equation:

$$TOF = \frac{F_{Ao}}{W} \frac{X_A}{CO_{uptake}} \quad (3)$$

where  $F_{Ao}$  is the molar rate of 1-propanethiol fed into the reactor ( $\mu\text{mol s}^{-1}$ ),  $W$  is the catalyst weight (g),  $CO_{uptake}$  is the uptake of chemisorbed CO ( $\mu\text{mol g}^{-1}$ ), and  $X_A$  is the 1-propanethiol conversion (%).

### 3. Results and discussion

#### 3.1. Characterization of the oxidic Ni/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, NiFe/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and Fe/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> catalysts

##### 3.1.1. XRD

The XRD patterns of the Ni-SDEA and Ni-IM catalysts and the  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> support are shown in Fig. 1(a). The diffraction peaks at  $2\theta = 36.9^\circ$ ,  $39.4^\circ$ ,  $46.0^\circ$  and  $66.8^\circ$  are ascribed to  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> (JCPDS No.

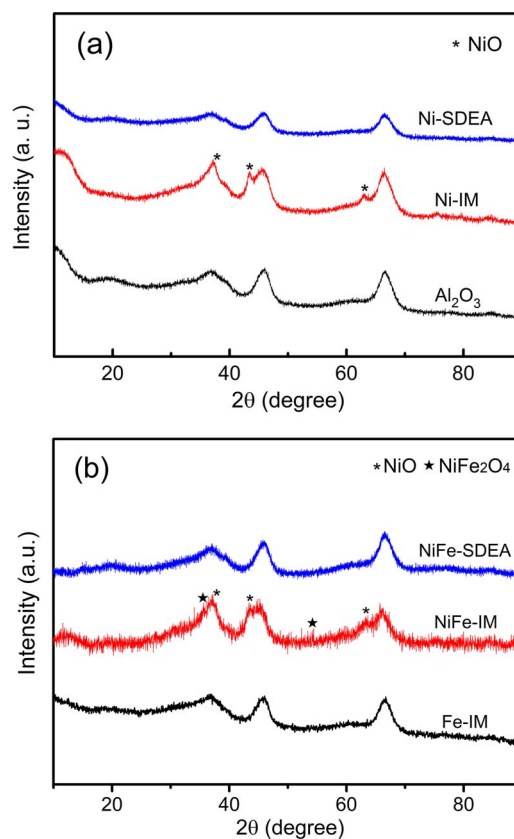


Fig. 1. XRD patterns of the oxidic Ni/Al<sub>2</sub>O<sub>3</sub> catalysts and Al<sub>2</sub>O<sub>3</sub> (a) and the oxidic NiFe/Al<sub>2</sub>O<sub>3</sub> and Fe/Al<sub>2</sub>O<sub>3</sub> catalysts (b).

29-1486) [32,33]. Only the Ni-IM catalyst possesses the NiO diffraction peaks at  $2\theta = 37.3^\circ$ ,  $43.4^\circ$  and  $62.8^\circ$  (JCPDS No. 44-1159) [34], indicating that it has a large particle size and a low dispersion of NiO. However, the Ni-SDEA catalyst has no bulk NiO crystallite peak in its XRD pattern, suggesting that it has a small particle size and a high dispersion of NiO. Compared with the Ni-IM catalyst prepared by the impregnation method, the Ni-SDEA catalyst prepared by the SDEA method has smaller NiO particles and better NiO dispersion.

The XRD patterns of the NiFe-SDEA, NiFe-IM and Fe-IM catalysts are shown in Fig. 1(b). There are no Fe<sub>2</sub>O<sub>3</sub> diffraction peaks in the XRD pattern of Fe-IM because of the low Fe loading. In addition, no peaks assigned to NiO and NiFe<sub>2</sub>O<sub>4</sub> crystallites are observed in the XRD pattern of NiFe-SDEA, demonstrating that the metal oxides are highly dispersed on the support. In the pattern of NiFe-IM, the peaks at  $2\theta = 37.3^\circ$ ,  $43.4^\circ$  and  $62.8^\circ$  are ascribed to the aggregation of NiO species (JCPDS No. 44-1159) [35], and the peaks at  $2\theta = 35.7^\circ$  and  $54.0^\circ$  are attributed to the bulk NiFe<sub>2</sub>O<sub>4</sub> species (JCPDS No. 54-0964) [36]. The above results reveal that the crystallites of metal oxides over NiFe-SDEA are smaller than those over NiFe-IM.

##### 3.1.2. XPS

The catalytic activity and selectivity of the thioetherification catalysts are affected by the number and chemical states of surface active metal sites. XPS characterization results can be used to determine the surface nickel components and dispersion degree. The high-resolution scans and corresponding fitting curves of Ni 2p spectra over the Ni-SDEA and Ni-IM catalysts are shown in Fig. 2. According to the peak area of the fitting curves, the calculated Ni/Al atomic ratios on the Ni-SDEA and Ni-IM catalysts are 0.085 and 0.074, respectively (Table 1). The above two catalysts were prepared with the same  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> support and almost equal NiO contents (about 14.0 wt.%, as determined by ICP); therefore, the Ni/Al atomic ratio can be used as a measurement to

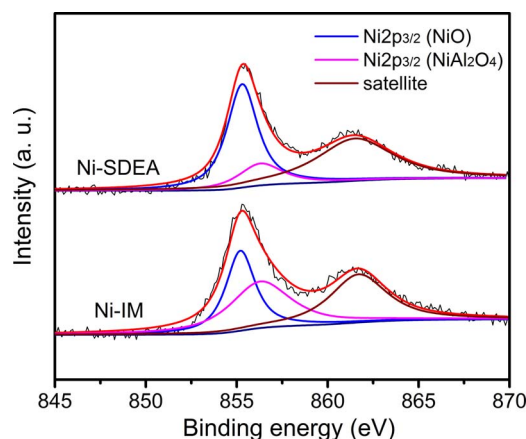
Fig. 2. Ni 2p XPS spectra of the oxidic Ni/Al<sub>2</sub>O<sub>3</sub> catalysts.

Table 1

Fitting results of XPS and NH<sub>3</sub>-TPD results on Ni-SDEA and Ni-IM catalysts.

Catalyst	Ni/Al	Ni 2p <sub>3/2</sub> (%)		Acid amount (relative content)
		NiO	NiAl <sub>2</sub> O <sub>4</sub>	
Ni-SDEA	0.085	76.7	23.3	1.00
Ni-IM	0.074	45.0	55.0	0.99

compare the dispersion degrees of Ni-SDEA and Ni-IM. The results show that Ni-SDEA has a higher Ni/Al atomic ratio than Ni-IM, indicating that the NiO particles on Ni-SDEA are highly dispersed.

The binding energy at 855.5 eV is assigned to the spin-orbit split lines of Ni 2p<sub>3/2</sub>, and the binding energy at 861.5 eV is ascribed to the shake-up satellites of Ni 2p<sub>3/2</sub> [37]. For the Ni 2p<sub>3/2</sub> energy level, two peaks are observed at 855.2 and 856.3 eV, which are attributed to octahedral Ni<sup>2+</sup> of the NiO species and tetrahedral Ni<sup>2+</sup> of the NiAl<sub>2</sub>O<sub>4</sub> phase, respectively [38]. According to the high-resolution scans and corresponding fitting curves of the Ni 2p<sub>3/2</sub> spectra, the relative concentrations of different Ni<sup>2+</sup> species were derived, as presented in Table 1. The relative contents of NiO and NiAl<sub>2</sub>O<sub>4</sub> species in Ni-SDEA are 76.7% and 23.3%, respectively, and the relative contents of NiO and NiAl<sub>2</sub>O<sub>4</sub> species in Ni-IM are 45.0% and 55.0%, respectively. Clearly, compared to Ni-IM, Ni-SDEA has a higher NiO content and a lower NiAl<sub>2</sub>O<sub>4</sub> content, indicating that the implementation of the SDEA method weakens the interaction between the  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> support and nickel species, thereby hindering the formation of inactive NiAl<sub>2</sub>O<sub>4</sub> species and increasing the relative content of NiO species.

The different Ni species on NiFe-SDEA and NiFe-IM are studied using the XPS survey spectra shown in Fig. 3(a). Compared with monometallic Ni-SDEA and Ni-IM, the new XPS peak at 855.6 eV is assigned to Ni in NiFe<sub>2</sub>O<sub>4</sub> species [39], and the binding energies of the Ni 2p<sub>3/2</sub> level shift to lower values, indicating the enhanced electron density of the nickel oxide species due to the addition of Fe<sub>2</sub>O<sub>3</sub> to Ni/Al<sub>2</sub>O<sub>3</sub> [40]. According to the high-resolution scans and corresponding fitting curves of the Ni 2p<sub>3/2</sub> spectra, the contents of different Ni species were derived, as presented in Table 2. The content of Ni in NiFe<sub>2</sub>O<sub>4</sub> species is 33.6% for NiFe-SDEA and 22.7% for NiFe-IM; the total content of Ni in NiO and NiFe<sub>2</sub>O<sub>4</sub> species, which are precursors of the active sites NiS<sub>x</sub> and NiFeS<sub>x</sub>, increases from 50.5% in NiFe-IM to 76.7% in NiFe-SDEA. In addition, the content of Ni in NiAl<sub>2</sub>O<sub>4</sub> species in NiFe-SDEA is much lower than that in NiFe-IM.

The Fe 2p<sub>3/2</sub> XPS spectra of the NiFe-SDEA, NiFe-IM and Fe-IM catalysts are exhibited in Fig. 3(b). On the surface of NiFe-SDEA, NiFe-IM and Fe-IM, the Fe species exist as NiFe<sub>2</sub>O<sub>4</sub>, FeO, Fe<sub>2</sub>O<sub>3</sub> and Fe-O-Al [41]. In the bimetallic NiFe catalysts, the binding energies of different Fe species exhibit slight changes compared with those in monometallic

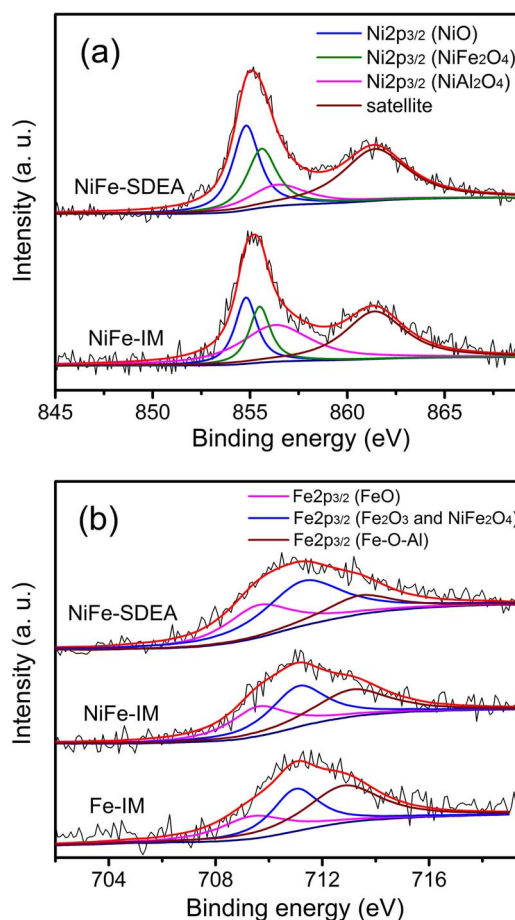


Fig. 3. Ni 2p XPS spectra of NiFe-SDEA and NiFe-IM (a) and Fe 2p XPS spectra of NiFe-SDEA, NiFe-IM and Fe-IM (b).

Table 2

XPS fitting results of NiFe-SDEA, NiFe-IM and Fe-IM.

Catalyst	Ni 2p <sub>3/2</sub> (%)			Fe 2p <sub>3/2</sub> (%)		
	Ni <sup>2+</sup> in NiO	Ni <sup>2+</sup> in NiFe <sub>2</sub> O <sub>4</sub>	Ni <sup>2+</sup> in NiAl <sub>2</sub> O <sub>4</sub>	Fe <sup>2+</sup> in FeO	Fe <sup>3+</sup> in Fe <sub>2</sub> O <sub>3</sub> and NiFe <sub>2</sub> O <sub>4</sub>	Fe <sup>3+</sup> in Fe-O-Al
NiFe-SDEA	43.1	33.6	23.4	30.8	50.9	18.4
NiFe-IM	27.8	22.7	49.5	28.8	37.9	33.3
Fe-IM	–	–	–	24.4	32.0	43.7

Fe/Al<sub>2</sub>O<sub>3</sub>, indicating that the chemical environment and electronic state of Fe are influenced by Ni [42]. The Fe 2p<sub>3/2</sub> spectra are decomposed according to the literature [43], and the relative contents of Fe in NiFe<sub>2</sub>O<sub>4</sub>, FeO, Fe<sub>2</sub>O<sub>3</sub> and Fe-O-Al species are listed in Table 2. Compared with Fe-IM, the contents of Fe in Fe-O-Al species of NiFe-SDEA and NiFe-IM decrease because the formation of NiFe<sub>2</sub>O<sub>4</sub> species involves Fe<sup>3+</sup> and Ni<sup>2+</sup> species, which can inhibit the generation of Fe-O-Al species. In addition, the content of Fe in Fe-O-Al decreases from 33.3% of NiFe-IM to 18.4% of NiFe-SDEA. These results demonstrate that the incorporation of SDBS into the preparation process weakens the metal-support interaction, thereby reducing the generation of inactive Fe-O-Al species and promoting the formation of more NiFe<sub>2</sub>O<sub>4</sub> species.

### 3.1.3. N<sub>2</sub> adsorption-desorption

The nitrogen adsorption-desorption isotherms and the pore diameter distributions of Ni/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, NiFe/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, Fe/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> indicate that the five catalysts and the support have mesoporous structures with concentrated pore size distributions (Figs. S3 and S4).



**Table 3**Textural properties results of Ni-SDEA, Ni-IM, NiFe-SDEA, NiFe-IM and Fe-IM catalysts and Al<sub>2</sub>O<sub>3</sub> support.

Sample	S <sub>g</sub> <sup>a</sup> (m <sup>2</sup> g <sup>-1</sup> )	V <sub>p</sub> <sup>b</sup> (cm <sup>3</sup> g <sup>-1</sup> )	D <sub>p</sub> <sup>c</sup> (nm)
Ni-SDEA	272	0.47	7.1
Ni-IM	238	0.34	6.2
NiFe-SDEA	259	0.41	6.8
NiFe-IM	221	0.29	6.0
Fe-IM	291	0.51	7.1
Al <sub>2</sub> O <sub>3</sub>	315	0.63	7.2

<sup>a</sup> BET specific surface area.<sup>b</sup> Pore volume.<sup>c</sup> Most probable pore size obtained by N<sub>2</sub> adsorption–desorption.

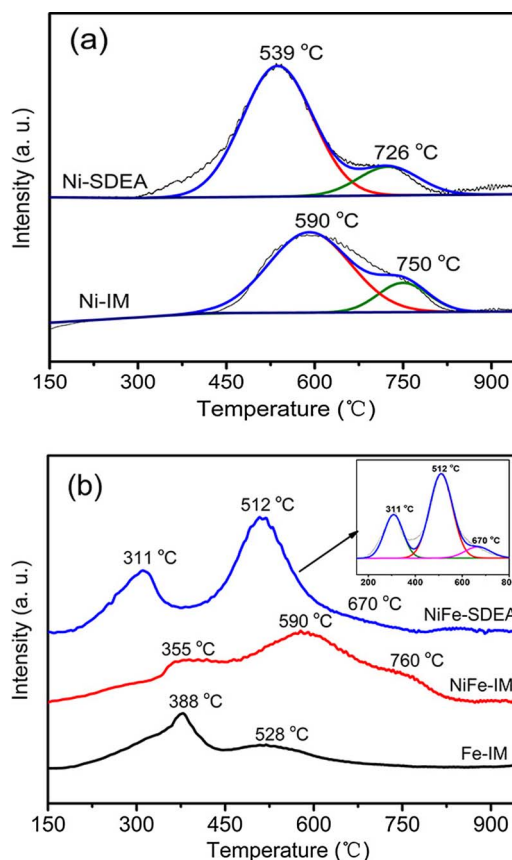
The most probable pore size of Ni-SDEA is higher than that of Ni-IM and close to that of  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> (Figs. S3 and S4), and the most probable pore size of NiFe-SDEA is higher than that of NiFe-IM, implying that the SDEA method has a negligible influence on the pore size of the  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> support.

The textural properties of the samples are listed in Table 3. Compared with the support, the pore volume and surface area of Ni/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, NiFe/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, and Fe/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> decrease. This is because during the calcination process, the supported active metal precursors yield deposited nanoparticles, which plug and block the pore channels of the support. Compared with the Ni-SDEA and NiFe-SDEA catalysts prepared by the SDEA method, the pore volume and surface area of Ni-IM and NiFe-IM catalysts prepared by the incipient wetness impregnation method decrease dramatically, this is because the supported metal nanoparticles are highly dispersed on Ni-SDEA and NiFe-SDEA, and the pore channels of the support are retained well. The introduction of Fe<sub>2</sub>O<sub>3</sub> into the Ni-SDEA and Ni-IM catalysts results in the decreased surface areas and pore volumes in them, due to the blockage of pores in the support by the incorporated Fe<sub>2</sub>O<sub>3</sub>. Compared with other catalysts, Fe-IM has a larger surface area and pore volume, which are attributed to the lower metal loading.

### 3.1.4. H<sub>2</sub>-TPR

To analyse the reducibility of metal oxides over the NiO/Al<sub>2</sub>O<sub>3</sub> catalysts, the Ni-SDEA and Ni-IM catalysts were evaluated using H<sub>2</sub>-TPR experiments, and the results are displayed in Fig. 4(a). All the samples have two H<sub>2</sub> consumption peaks in the range of 400–820 °C. The peaks at low temperature over these two catalysts correspond to the reduction of NiO species strongly interacting with  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> [20], and the peaks at high temperature over these two catalysts are attributed to the reduction of NiAl<sub>2</sub>O<sub>4</sub> spinels [39,44,45]. The H<sub>2</sub> consumption peaks at low and high temperatures of Ni-SDEA are 539 and 726 °C, respectively, while those of Ni-IM are 590 and 750 °C, demonstrating that the metal-support interaction is weaker over Ni-SDEA than over Ni-IM. The total hydrogen consumptions in the H<sub>2</sub>-TPR patterns of Ni-SDEA and Ni-IM are quantified to be 1.426 and 1.125 mmol g<sup>-1</sup>, respectively. The corresponding H<sub>2</sub> consumption of the peak at low temperature was obtained by peak decomposing. The H<sub>2</sub> consumptions over Ni-SDEA and Ni-IM at low temperature are 1.184 and 0.909 mmol g<sup>-1</sup>, respectively, which is consistent with the higher NiO quantity and smaller particles in Ni-SDEA than in Ni-IM.

The H<sub>2</sub>-TPR profiles of NiFe-SDEA, NiFe-IM and Fe-IM are presented in Fig. 4(b). The profile of Fe-IM shows two reduction peaks at 388 and 528 °C, which are ascribed to the reduction of  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> to Fe<sub>3</sub>O<sub>4</sub> and the reduction of Fe<sub>3</sub>O<sub>4</sub> to  $\alpha$ -Fe, respectively [46,47]. For the NiFe-SDEA catalysts, the peak at 311 °C is attributed to the reduction of  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> to Fe<sub>3</sub>O<sub>4</sub>, and the peak at 512 °C corresponds to the reduction of Fe<sub>3</sub>O<sub>4</sub> to  $\alpha$ -Fe, the reduction of NiO species weakly interacting with  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> to Ni, and the reduction of NiFe<sub>2</sub>O<sub>4</sub> to Ni and  $\alpha$ -Fe, the peak at 670 °C corresponds to the reduction of NiO species strongly interacting with  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> [48]. For the NiFe-IM catalysts, the peak at 355 °C is attributed to

Fig. 4. H<sub>2</sub>-TPR spectra of Ni-SDEA and Ni-IM (a) and NiFe-SDEA, NiFe-IM and Fe-IM (b).

the reduction of  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> to Fe<sub>3</sub>O<sub>4</sub>; the peak at 590 °C corresponds to the reduction of Fe<sub>3</sub>O<sub>4</sub>, NiFe<sub>2</sub>O<sub>4</sub>, and NiO species strongly interacting with  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> to  $\alpha$ -Fe, Ni and  $\alpha$ -Fe, and Ni, respectively; and the peak at 760 °C corresponds to the reduction of NiAl<sub>2</sub>O<sub>4</sub> to Ni [48]. Compared with NiFe-IM, the hydrogen consumption peaks of NiFe-SDEA shift to much lower temperatures. The above results indicate that SDBS can effectively prevent a strong interaction between the metal oxides and  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> support. As a result, the generation of NiAl<sub>2</sub>O<sub>4</sub> spinel phase through strong interaction with the support is inhibited, and more metal oxides are formed. Therefore, nickel species are more easily reduced and sulfided. Compared with the monometallic Ni-SDEA catalyst, the introduction of Fe promotes the reduction of Ni species in the bi-metallic NiFe-SDEA catalyst, because the interaction between NiO and Fe species can form NiFe<sub>2</sub>O<sub>4</sub>, which is more easily reduced than NiO [20,49].

### 3.1.5. NH<sub>3</sub>-TPD

The NH<sub>3</sub>-TPD results indicate that Ni-SDEA and Ni-IM have almost the same acid strength (Fig. S5). The relative acid amounts of the two catalysts, which are listed in Table 1, are also almost the same.

### 3.1.6. Origin of highly dispersed NiO nanoparticles on Ni-SDEA

The Ni-SDEA catalyst prepared by the SDEA method has superior NiO dispersion, which is attributed to the de-agglomeration effect of SDBS (Fig. 5). The point of zero charge (PZC) of Al<sub>2</sub>O<sub>3</sub> is pH = 8.4 [50,51], and hence, the Al<sub>2</sub>O<sub>3</sub> surface has positive charges with a zeta potential of 18.3 mV at pH 5.0. Thus, electrostatic repulsion occurs between the positively charged Ni<sup>2+</sup> ions and the electropositive Al<sub>2</sub>O<sub>3</sub> surface, and it is therefore difficult for Ni<sup>2+</sup> ions to adsorb onto the Al<sub>2</sub>O<sub>3</sub> surface. After the introduction of SDBS, the negatively charged SDBS<sup>-</sup> ions could form self-assembled bilayers on the Al<sub>2</sub>O<sub>3</sub> surface; one negative charge of these bilayers are connected with the electropositive

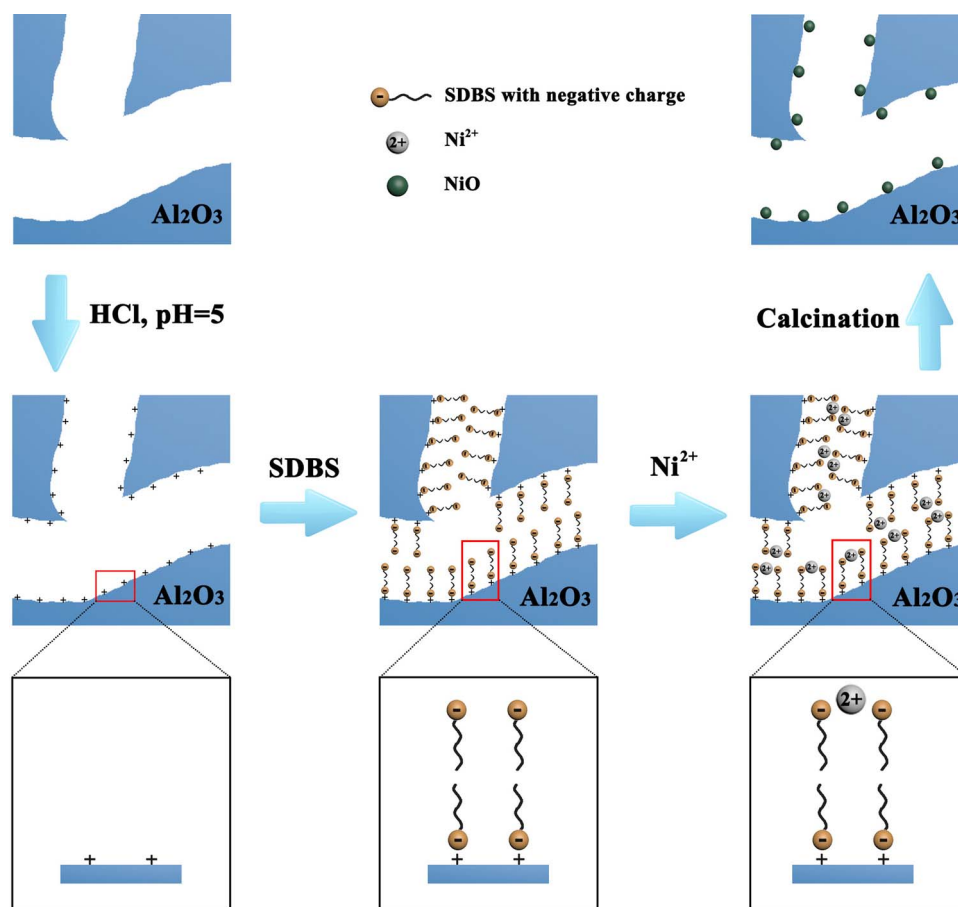


Fig. 5. Schematic diagram of the preparation principle of Ni-SDEA.

$\text{Al}_2\text{O}_3$  surface, and the other negative charge is exposed, as verified by the zeta potential of  $-13.7$  mV on the surface of  $\text{DBS}^-$ -modified alumina ( $\text{Al}_2\text{O}_3\text{-DBS}$ ) (Fig. 5). After the addition of  $\text{Ni}^{2+}$  ions, the electrostatic interaction between the  $\text{Ni}^{2+}$  ions and the electronegative  $\text{Al}_2\text{O}_3\text{-DBS}$  surface induces the anchoring of  $\text{Ni}^{2+}$  ions on  $\text{Al}_2\text{O}_3\text{-DBS}$  (Fig. 5). Furthermore, the long-chain alkyl groups in the bilayers can isolate the metals from the  $\text{Al}_2\text{O}_3$  support, weakening the metal-support interaction and thus inhibiting the formation of nickel-aluminium spinels. During calcination in an air atmosphere, the slow combustion of surfactant produces a gaseous mixture that can be considered a protective barrier to inhibit the aggregation of metal species [52,53]. Meanwhile, a small amount of residual carbonaceous species is detected in the as-prepared Ni-SDEA catalyst (2.62 wt.%), the residual carbonaceous species plays an important role in isolating nickel species and preventing them from agglomeration [31].

In the conventional impregnation process, the acid solution is able to dissolve part of alumina, and thereby the surface hydroxyl-type coprecipitation of  $\text{Ni}^{2+}$  ions with  $\text{Al}^{3+}$  is formed. The intimate contact between Ni and Al gives easily rise to  $\text{NiAl}_2\text{O}_4$  under calcinations [54,55], as demonstrated by the above XPS characterization. As a result, the dispersion of supported NiO decreases, and Ni-IM thus possesses a low dispersion of large-sized NiO nanoparticles and a high content of nickel-aluminium spinels.

### 3.2. Characterization of the sulfided $\text{Ni}/\gamma\text{-Al}_2\text{O}_3$ , $\text{NiFe}/\gamma\text{-Al}_2\text{O}_3$ and $\text{Fe}/\gamma\text{-Al}_2\text{O}_3$ catalysts

#### 3.2.1. HRTEM

Representative HRTEM micrographs and the corresponding particle size distributions of supported metal nanoparticles over sulfided  $\text{Ni}/\gamma\text{-Al}_2\text{O}_3$  and  $\text{NiFe}/\gamma\text{-Al}_2\text{O}_3$  are shown in Figs. 6 and 7. White squares

denote some of the dark regions corresponding to Ni species (or  $\text{NiS}_x$  and  $\text{NiFeS}_x$  species) supported on the  $\gamma\text{-Al}_2\text{O}_3$  surface (determined by EDS). In Fig. 6(a) and (b), the nanoparticles of the Ni species supported on NiS-SDEA are evenly dispersed with a concentrated size distribution between 2 and 4 nm, indicating the high dispersion of Ni nanoparticles over NiS-SDEA. However, the Ni nanoparticles supported on NiS-IM are aggregated into large clusters with a concentrated size distribution between 7 and 11 nm, as shown in Fig. 6(c) and (d), demonstrating the low dispersion of Ni nanoparticles over NiS-IM. According to Fig. 6(b) and (d), the mean sizes of the Ni nanoparticles over NiS-SDEA and NiS-IM are 2.8 and 7.9 nm, respectively. This result indicates that SDBS plays an important role in reducing the aggregation of Ni nanoparticles during the calcination and sulfidation steps.

In Fig. 7(a), the nanoparticles of NiFe species supported on NiFeS-SDEA are highly dispersed with an average particle size of 3.7 nm, demonstrating that the incorporation of Fe has little influence on the dispersion of the supported metal. NiFeS-IM possesses an average particle size of 11.5 nm, which is larger than that of NiFeS-SDEA. Additionally, the aggregation of the metal nanoparticles on NiFeS-IM is obvious, and the dispersion is poor. This result indicates that NiFeS-SDEA prepared by the SDEA method has considerably more  $\text{NiS}_x$  and  $\text{NiFeS}_x$  species than NiFeS-IM, which implies the superior thioetherification activity of NiFeS-SDEA. The HRTEM images of the used NiFeS-SDEA and NiFeS-IM catalysts demonstrate that the size and dispersion of metal nanoparticles over NiFeS-SDEA and NiFeS-IM are not changed after reaction for 144 h (Fig. S6).

#### 3.2.2. XPS

Ni 2p XPS spectra of sulfided  $\text{Ni}/\gamma\text{-Al}_2\text{O}_3$ ,  $\text{NiFe}/\gamma\text{-Al}_2\text{O}_3$  and  $\text{Fe}/\gamma\text{-Al}_2\text{O}_3$  are presented in Fig. 8. The binding energy at 853.2 eV is ascribed to the  $2p_{3/2}$  level of  $\text{NiS}_x$  [56]. Compared with NiS-SDEA and

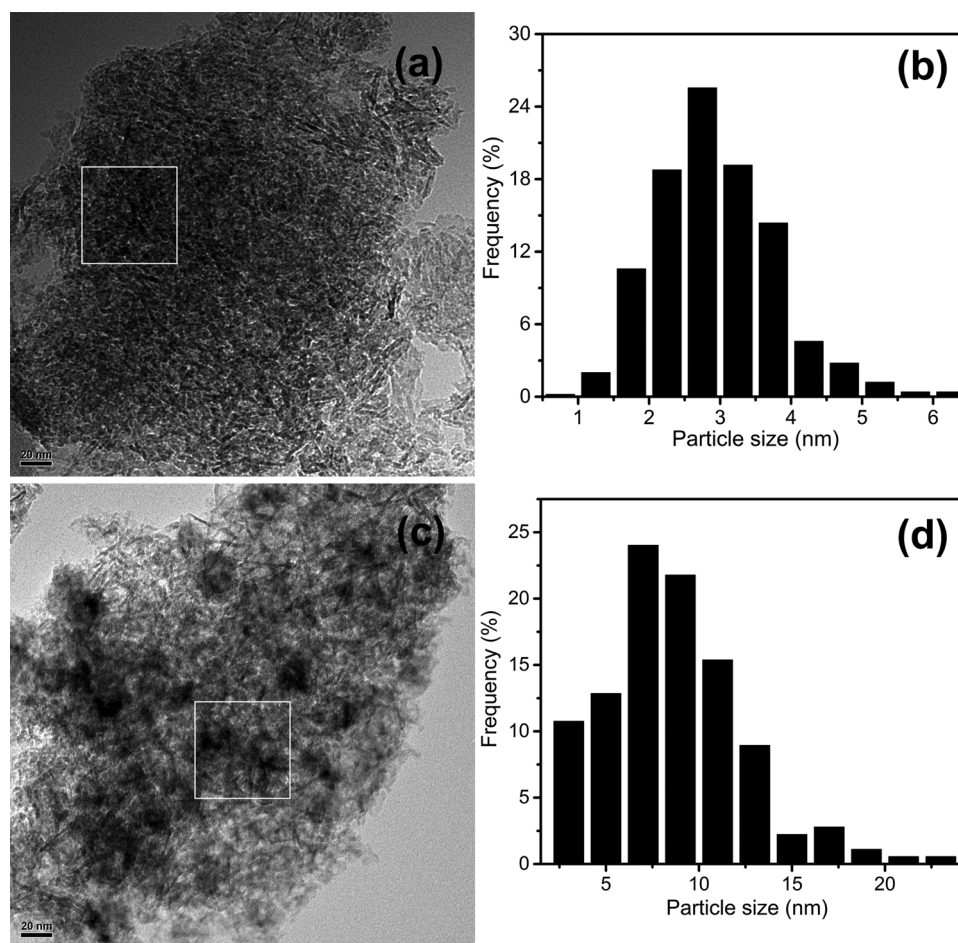


Fig. 6. HRTEM images and nanoparticle size distributions of NiS-SDEA (a and b) and NiS-IM (c and d).

NiS-IM, there is a new XPS peak at 853.8 eV attributed to Ni in NiFeS<sub>x</sub> species in NiFeS-SDEA and NiFeS-IM [57]. The fitting results of the XPS spectra in Table 4 show that the content of NiS<sub>x</sub> in NiS-IM is only 15.6% due to the strong interaction between Ni<sup>2+</sup> and  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, which thus causes the low sulfidation degree of the nickel species. However, the content of NiS<sub>x</sub> in NiS-SDEA is 34.6%, 2.22 times greater than that in NiS-IM, indicating that SDBS addition promotes the sulfidation of nickel species. The content of NiAl<sub>2</sub>O<sub>4</sub> decreases from 57.8% in NiS-IM to 35.9% in NiS-SDEA, illustrating that the surfactant SDBS greatly inhibits the formation of inactive NiAl<sub>2</sub>O<sub>4</sub> species. The contents of Ni in NiS<sub>x</sub> and NiFeS<sub>x</sub> increase from 16.6% and 11.0% for NiFeS-IM to 29.9% and 17.0% for NiFeS-SDEA, respectively (Table 5), demonstrating that the SDEA method promotes the formation of active sites for the thioetherification reaction.

Fig. 9 shows the experimental and fitted XPS spectra of S 2p for sulfided Ni/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, NiFe/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and Fe/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>. The binding energies at 161.6, 162.3 and 163.5 eV are attributed to the 2p<sub>3/2</sub> level of the monosulfide (S<sup>2-</sup>), disulfide (S<sub>2</sub><sup>2-</sup>), and polysulfide (S<sub>n</sub><sup>2-</sup>) species, respectively [58]. According to the calculated peak areas of fitted curves, the relative concentrations of different S species were derived, as presented in Tables 4 and 5. In NiS-SDEA and NiS-IM, the predominant S species are S<sup>2-</sup> and S<sub>2</sub><sup>2-</sup>; the contents of S<sup>2-</sup> and S<sub>2</sub><sup>2-</sup> species in NiS-SDEA are 33.7 and 43.4%, whereas in NiS-IM the content of S<sup>2-</sup> species increases to 53.2%, and the content of S<sub>2</sub><sup>2-</sup> species decreases to 30.8%. The relative contents of S<sub>2</sub><sup>2-</sup> in NiFeS-SDEA and NiFeS-IM are higher than those in NiS-SDEA, NiS-IM and FeS-IM. Compared with NiFeS-IM prepared by impregnation, NiFeS-SDEA has more S<sub>2</sub><sup>2-</sup> species and less S<sup>2-</sup> species bonded to metal atoms.

### 3.3. Catalytic activity of the sulfided Ni/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, NiFe/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and Fe/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> catalysts

The catalytic performances of the sulfided Ni/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, NiFe/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and Fe/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> catalysts for the thioetherification of 1-propanethiol and isoprene are shown in Table 6. NiS-SDEA has a mercaptan removal ratio of 90.2%, which is much higher than the 74.9% removal ratio obtained over NiS-IM. The mercaptan removal ratio of NiFeS-SDEA (99.5%) is higher than that of NiFeS-IM (85.1%). The mercaptan removal ratio of FeS-IM is as low as 43.6%, demonstrating the inferior thioetherification activity of this catalyst. The TOF value of NiS-SDEA is higher than that of NiS-IM (Table 6), indicating the better catalytic activity of NiS-SDEA. In view of the fact that the incorporation of Fe into the monometallic nickel catalysts improves the thioetherification activity, the TOF of the bimetallic catalysts are displayed in Table 6. The TOF of NiFeS-SDEA is higher than that of NiFeS-IM (Table 6), indicating the better catalytic activity of NiFeS-SDEA. NiS-SDEA, NiS-IM, NiFeS-SDEA, NiFeS-IM and FeS-IM have constant mercaptan removal ratio and olefin conversion, demonstrating their good activity stability (Figs. S7 and S8).

Furthermore, the olefin conversion over NiFeS-SDEA is 1.3%, which is slightly higher than those over NiS-SDEA, NiS-IM, NiFeS-IM and FeS-IM. The above results demonstrate that NiFeS-SDEA has an excellent mercaptan removal ratio and very low olefin conversion, indicating its outstanding selectivity for mercaptan removal.

The catalytic performances of the NiFeS-SDEA catalyst for the thioetherification of butanethiol isomers (1-butanethiol, iso-butanethiol and t-butanethiol) and isoprene are presented in Fig. 10. The mercaptan removal ratio over NiFeS-SDEA increases with the following sequence:



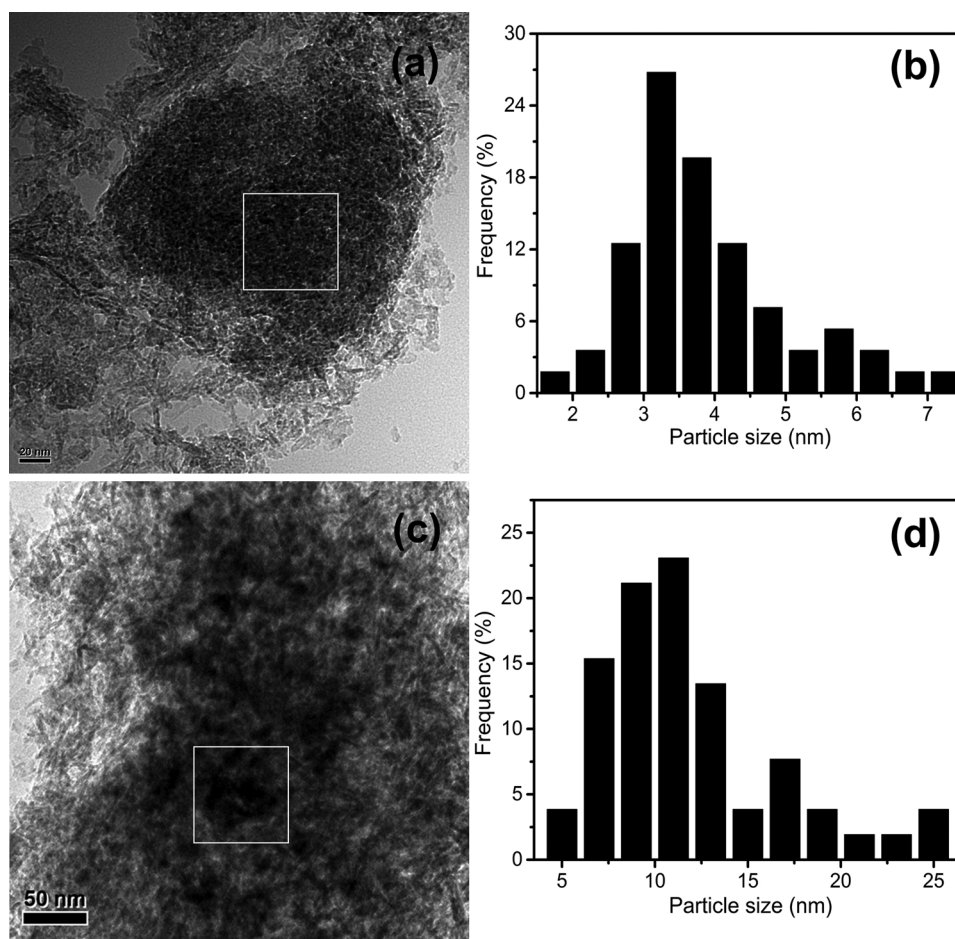


Fig. 7. HRTEM images and nanoparticle size distributions of NiFeS-SDEA (a and b) and NiFeS-IM (c and d).

t-butanethiol < iso-butanethiol < 1-butanethiol. Shen et al. reported the free-radical addition mechanism for thioetherification reaction [13], in which the steric hindrance of mercaptans is an important factor affecting the thioetherification activity. The steric hindrance of the mercaptans for the –SH group increases with the following sequence: 1-butanethiol < iso-butanethiol < t-butanethiol [59], leading to more difficulty in C–S or S–H cleavage with greater steric hindrance around the –SH group in mercaptan.

The thioetherification performances of the NiFeS-SDEA catalyst for the mercaptans with different alkyl chain lengths (1-propanethiol, 1-butanethiol and 1-pentanethiol) are presented in Fig. 11. The mercaptan removal ratio decreases with the increase in the number of carbon atoms in the alkyl chain. This is because with the increase of alkyl chain length, the steric hindrance around the –SH group in mercaptan increases [60], and thereby the mercaptan with longer alkyl chain has worse reactivity.

### 3.4. Structure–activity correlation

The above thioetherification assessment results have demonstrated that catalyst NiS-SDEA has higher thioetherification activity than catalyst NiS-IM. To understand the different activities, it is necessary to correlate the thioetherification activities of the two catalysts with their structures. Since NiS-SDEA and NiS-IM have almost the same NiO loading, acid strength and acid amount (Fig. S5 and Table 1), the difference between the thioetherification activities of the two catalysts is related to the quantity and type of active sites. The enhanced activity of NiS-SDEA can be interpreted as follows: first, the dispersion of Ni on NiS-SDEA and Ni-IM are 17.9% and 8.2%, respectively. With a similar NiO

loading (13.8 wt.% for NiS-SDEA and 14.0 wt.% for NiS-IM, determined via ICP analysis), the higher dispersion of nickel on NiS-SDEA than on NiS-IM indicates that the former catalyst has smaller nickel particles than the latter catalyst, as demonstrated by the HRTEM images in Fig. 6. The number of active NiS<sub>x</sub> sites on NiS-SDEA is greater than that on NiS-IM due to the smaller nanoparticles of Ni species and the higher dispersion of Ni nanoparticles on NiS-SDEA (Fig. 6). Second, among the S<sup>2−</sup>, S<sub>2</sub><sup>2−</sup> and S<sub>n</sub><sup>2−</sup> species, the binding energy of S<sup>2−</sup> species is the lowest (Fig. 9), indicating that the S<sup>2−</sup> species have the highest electron density and that accordingly, the Ni species bonded to S<sup>2−</sup> species also have the highest electron density. Furthermore, the sulfur atom in mercaptan and the C=C double bond in olefins are electron rich [61]; therefore, the adsorption of the reactant molecules on the NiS species is weak, and thus, the activation of the reactant molecules is poor. As a consequence, the catalyst with more NiS species has an inferior activity for mercaptan removal. Among the three sulfur species, the binding energy of the S<sub>n</sub><sup>2−</sup> species is the highest, demonstrating that the S<sub>n</sub><sup>2−</sup> species have the lowest electron density and that accordingly, the Ni species bonded to S<sub>n</sub><sup>2−</sup> species also have the lowest electron density. Therefore, the reactant molecules (mercaptan and diolefin) can be strongly adsorbed on the NiS<sub>n</sub> species, and because of the electron-rich nature of the sulfur atom in thioethers, it is difficult for the generated thioether compounds to desorb from these active sites. As a consequence, the catalyst with more NiS<sub>n</sub> species has an inadequate activity for mercaptan removal. Due to the electron migration of the Ni species with medium electron deficiency bonded to S<sub>2</sub><sup>2−</sup>, the electron density of S<sub>2</sub><sup>2−</sup> species is optimal for the adsorption of reactant molecules and the desorption of products; consequently, the catalyst with more NiS<sub>2</sub> species should exhibit superior activity for mercaptan



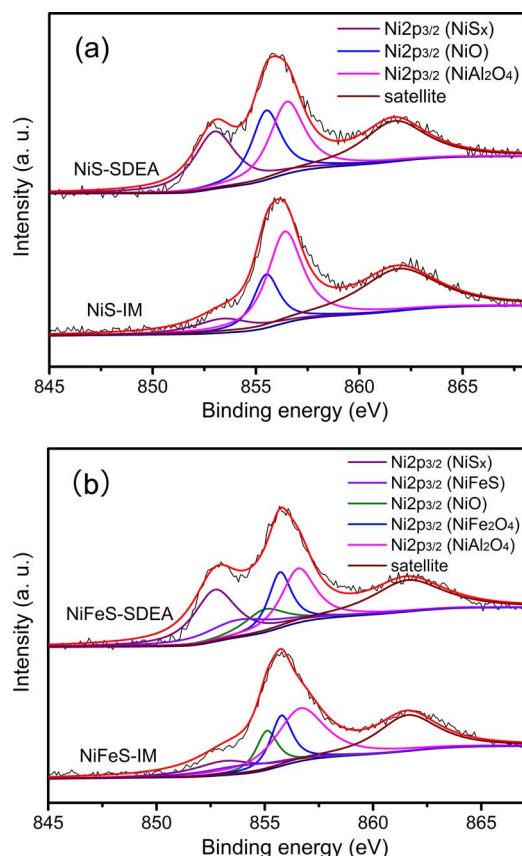


Fig. 8. Ni 2p XPS spectra of NiS-SDEA and NiS-IM (a) and NiFeS-SDEA and NiFeS-IM (b).

**Table 4**  
XPS fitting results of NiS-SDEA and NiS-IM.

Catalyst	Ni 2p <sub>3/2</sub> (%)			S 2p <sub>3/2</sub> (%)		
	NiS <sub>x</sub>	NiO	NiAl <sub>2</sub> O <sub>4</sub>	S <sup>2-</sup>	S <sub>2</sub> <sup>2-</sup>	S <sub>n</sub> <sup>2-</sup>
NiS-SDEA	34.6	29.5	35.9	33.7	43.4	22.9
NiS-IM	15.6	26.7	57.8	53.2	30.8	16.0

**Table 5**  
XPS fitting results of NiFeS-SDEA, NiFeS-IM and FeS-IM.

Catalyst	Ni 2p <sub>3/2</sub> (%)		S 2p <sub>3/2</sub> (%)		
	NiS <sub>x</sub>	NiFeS	S <sup>2-</sup>	S <sub>2</sub> <sup>2-</sup>	S <sub>n</sub> <sup>2-</sup>
NiFeS-SDEA	29.9	17.0	24.1	58.4	17.5
NiFeS-IM	16.6	11.0	37.2	49.2	13.7
FeS-IM	–	–	13.0	23.2	63.8

removal. As seen in Table 4, the content of NiS<sub>2</sub> species over NiS-SDEA is higher than that over NiS-IM, supporting the higher mercaptan removal ratio over NiS-SDEA than over NiS-IM.

Because the introduction method and content of Fe in the two NiFe catalysts are the same, the greater catalytic activity of catalyst NiFeS-SDEA is attributed to the SDEA method used for loading Ni species. On the one hand, the introduction of SDBS is advantageous for the formation and dispersion of uniform Ni and NiFe species (demonstrated by the HRTEM images in Fig. 7), and the resulting smaller and more highly dispersed Ni and NiFe nanoparticles over NiFeS-SDEA than over NiFeS-IM (Fig. 7) provide a higher content of active sites. On the other hand, the SDEA method can inhibit the formation of inactive NiAl<sub>2</sub>O<sub>4</sub> species (Fig. 4(b)), which increases the content of active NiS<sub>x</sub> and NiFeS<sub>x</sub> sites.

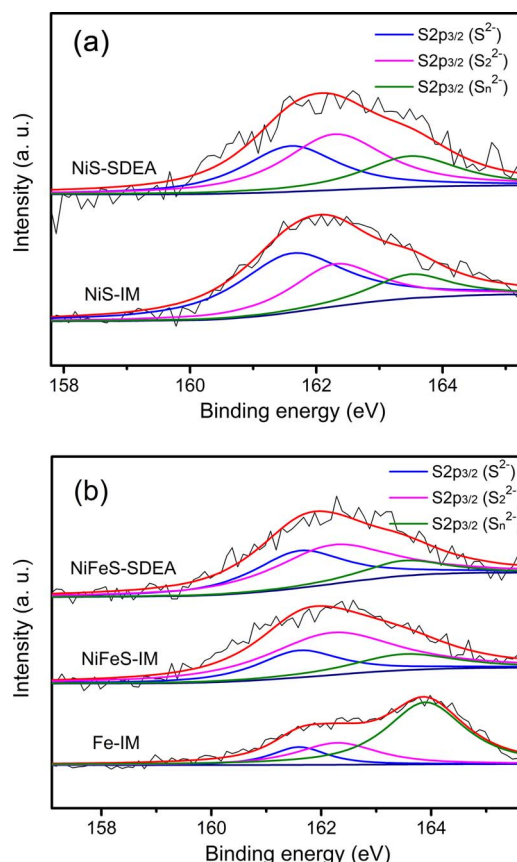


Fig. 9. S 2p XPS spectra of NiS-SDEA and NiS-IM (a) and NiFeS-SDEA, NiFeS-IM and FeS-IM (b).

**Table 6**  
Thioetherification reaction results over the Ni, NiFe and Fe catalysts.

Catalyst	mercaptan removal ratio (%)	olefin conversion (%)	TOF (10 <sup>-3</sup> s <sup>-1</sup> )
NiS-SDEA	90.2	1.1	2.65
NiS-IM	74.9	0.7	1.82
NiFeS-SDEA	99.5	1.3	3.32
NiFeS-IM	85.1	0.9	2.76
FeS-IM	43.6	0.5	–

As shown in Table 5, the content of S<sub>2</sub><sup>2-</sup> species over NiFeS-SDEA is 58.4%, which is higher than 49.2% over NiFeS-IM. Over NiFeS-SDEA, the Fe atoms interact with the highly dispersed NiS<sub>x</sub> species that possess a higher content of active NiS<sub>2</sub> sites (Table 5), and thereby the active NiFeS<sub>x</sub> sites over NiFeS-SDEA are mainly composed of NiFeS<sub>2</sub> species (Table 5). Among the NiS<sub>x</sub> and NiFeS<sub>x</sub> active sites, the NiS and NiFeS active sites have an inferior activity for mercaptan removal, because the Ni and NiFe bonded to S<sup>2-</sup> species have the highest electron density (Fig. 9) and resultant poor activation ability for mercaptan; the NiS<sub>n</sub> and NiFeS<sub>n</sub> active sites have a low activity for mercaptan removal due to the lowest electron density of the Ni and NiFe bonded to S<sub>n</sub><sup>2-</sup> species (Fig. 9), resulting in the difficult desorption of the generated thioether compounds from these active sites; the NiS<sub>2</sub> and NiFeS<sub>2</sub> active sites exhibit superior activity for mercaptan removal because of the optimal activation of reactant molecules and the easy desorption of product molecules. It is the higher content of NiS<sub>2</sub> and NiFeS<sub>2</sub> species over NiFeS-SDEA than over NiFeS-IM (Table 5) that leads to the better mercaptan removal over NiFeS-SDEA than over NiFeS-IM. The above two effects greatly improve the thioetherification activity of NiFeS-SDEA.

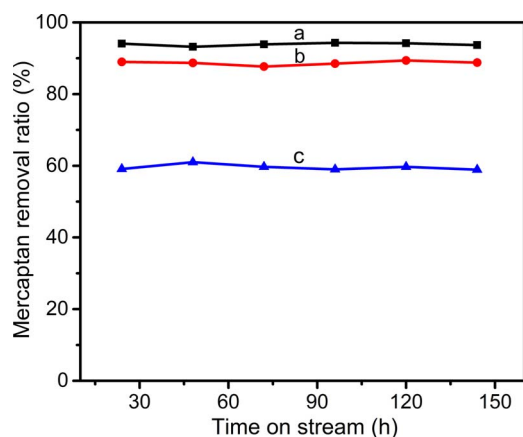


Fig. 10. Thioetherification performances of NiFeS-SDEA for 1-butanethiol (a), iso-butanethiol (b) and t-butanethiol (c).

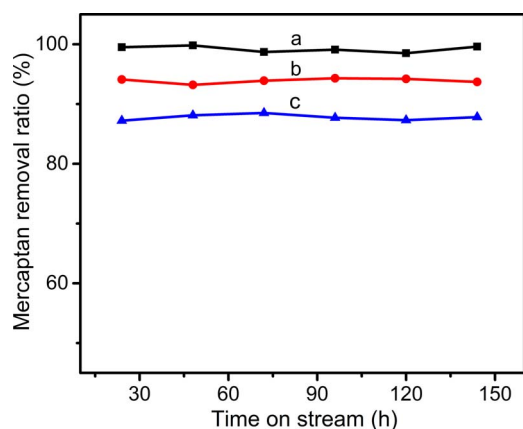


Fig. 11. Thioetherification performances of NiFeS-SDEA for 1-propanethiol (a), 1-butanethiol (b) and 1-pentanethiol (c).

The product distributions of NiS-SDEA and NiS-IM are listed in Table 7. The sulfur types in the product obtained over the two catalysts are similar: the main type of sulfur-containing compound is  $C_3SC_5$  (pathway I, IV and VI), and the product also contains some thioether  $C_3SC_3$  (pathway III) and  $C_5SC_5$  (pathway V), as well as dimethyl sulfide species  $C_3SSC_3$  (pathway II). According to the above results, the reaction pathways for the thioetherification of 1-propanethiol can be inferred as follows (Fig. 12): S–H bond scission of 1-propanethiol generates dissociated  $C_3S^*$  and  $*H$  groups [62,63]; subsequently, the  $C_3S^*$  species interacts with  $C_5^*$  that originate from the activation of adsorbed isoprene, and thus,  $C_3SC_5$  species are generated (pathway I). Meanwhile, some dimethyl sulfide species,  $C_3SSC_3$ , are formed via the coupling of two  $C_3S^*$  species on active  $NiS_x$  sites (pathway II). In addition, the breaking of the C–S bond in 1-propanethiol also occurs, generating dissociated  $C_3^*$  and  $*SH$ ; the former species interacts with dissociated  $C_3S^*$  and generates  $C_3SC_3$  (pathway III). Todorova et al. proposed that the generated  $*SH$  could interact with the adsorbed olefin intermediate

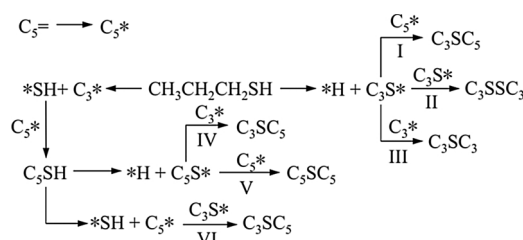


Fig. 12. Thioetherification reaction network of 1-propanethiol.

through a reverse reaction and produce new mercaptans [64]; thus,  $*SH$  could interact with  $C_5^*$  and form pentanethiol  $C_5SH$ , and then  $C_5SH$  could participate in the above reactions (S–H bond scission and C–S bond scission) immediately. The S–H bond scission generates dissociated  $C_5S^*$  and  $*H$  groups, and  $C_5S^*$  interacts with  $C_3^*$  and  $C_5^*$  to form  $C_3SC_5$  (pathway IV) and  $C_5SC_5$  (pathway V), respectively; C–S bond scission generates  $C_5^*$  and  $*SH$  species, and  $C_5^*$  interacts with  $C_3S^*$  to form  $C_3SC_5$  (pathway VI).

The contents of  $C_3SSC_3$ ,  $C_3SC_3$  and  $C_5SC_5$  over NiS-IM are higher than those over NiS-SDEA, indicating that NiS-IM has higher content of  $C_3S^*$  and  $C_5S^*$  species in reaction than NiS-SDEA. Thus, NiS-IM exhibits better ability to cleave the S–H bond of mercaptan than NiS-SDEA.  $C_3SC_5$  can be formed by the pathways I, IV and VI, and the pathways I and IV are the S–H bond scission reaction [13]. Because NiS-SDEA has inferior ability to cleave the S–H bond of mercaptan compared with NiS-IM, the higher content of  $C_3SC_5$  over NiS-SDEA than that over NiS-IM should be attributed to the enhanced pathway VI that is the C–S bond scission reaction [13]. Thus, NiS-SDEA has better ability to cleave the C–S bond of mercaptan than NiS-IM. According to the XPS characterization results, the content of  $S^{2-}$  species in NiS-SDEA is higher than that in NiS-IM, whereas the content of  $S^{2-}$  species in NiS-SDEA is lower than that in NiS-IM. The above reaction results suggest that a high content of  $S^{2-}$  species enhances the C–S bond scission of mercaptan, while a high content of  $S^{2-}$  species improves the S–H bond scission of mercaptan.

#### 4. Conclusions

A novel SDBS-assisted equilibrium adsorption method is proposed to prepare monometallic Ni/ $Al_2O_3$  and Fe-promoted NiFe/ $Al_2O_3$  catalysts with high metal dispersion and a weak metal-alumina interaction. In this method, nickel cations are anchored onto the electronegative DBS<sup>−</sup>-modified  $Al_2O_3$  support ( $Al_2O_3$ -DBS), and the aggregation of Ni nanoparticles during calcination is prevented by the isolation effect of carbonaceous species. Furthermore, this method weakens the metal-support interaction and reduces the formation of nickel-aluminium spinels because it decreases the direct interaction between Ni species and the alumina support. As a consequence, the active Ni and NiFe sites are highly dispersed on the surface of  $Al_2O_3$ -DBS with an enhanced reducibility and sulfurization degree. The corresponding Ni-based catalysts prepared by this method exhibit much higher activity and selectivity for mercaptan removal than their counterparts prepared by the conventional impregnation method.

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#### Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.apcatb.2018.02.053>.

Table 7  
Product distributions of NiS-SDEA and NiS-IM catalysts.

Catalyst	Product selectivity <sup>a</sup> (%)			
	$C_3SC_3$	$C_3SC_5$	$C_3SSC_3$	$C_5SC_5$
NiS-SDEA	3.74	85.78	3.55	6.93
NiS-IM	6.19	75.64	7.19	10.98

<sup>a</sup> Determined at about 50% of the 1-propanethiol conversion by changing liquid hourly space velocity.

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